GRASS LINED CHANNEL DESIGN EXAMPLE USING HEC-15

Given the following channel geometry, soil conditions, grade, and design flow, determine if a grass lining that will be maintained in good condition in the spring and summer months (the main storm seasons) is an acceptable channel liner.

Given:

Geometry: Triangular (V-ditch), B = 0.0 ft, Z = 4

Soil: Clayey sand (SC classification)

PI = 16

e = 0.35

Soil Type: Cohesive

Grass: Vegetation Type: Turf

Retardance Class: Type C

Grass Height, h = 0.67 ft

Grass Condition: Good

Grass Density-Stiffness Coefficient, C_s, = 9.0

Slope: 2.0 percent

Flow: 15 ft^3/s

Solution:

Use the procedure in Section 3.1, HEC-15 for a straight channel.

Step 1. Channel slope, soil type, geometry, and discharge are given.

Step 2. Assume an initial depth = 1.0 ft.

From the geometric relationship of a trapezoid (see HEC-15, Appendix B):

A (Area) = $Bd + Zd^2 = 0.0(1.0) + 4(1.0)^2 = 4.00\ ft^2$

P (Wetted Perimeter) = $B + 2d(Z^2 + 1)^{1/2} = 0.0 + 2(1.0)(4^2 + 1)^{1/2} = 8.25$ ft

R (Hydraulic Radius) = A/P = (4.00)/(8.25) = 0.485 ft

Step 3. To estimate n, determine the applied shear stress on the grass lining and the discharge:

$\tau_o = \gamma R S_o = 62.4(0.485)(0.02) = 0.61\ lb/ft^2$ (Refer to FDM 13-30-10, Equation 2)

Determine a Manning's n from FDM 13-30-15, Equation 12 with

$C_n = 0.237(C_s)^{0.1}(h)^{0.528} = 0.237(9.0)^{0.1}(0.67)^{0.528} = 0.238$ (HEC-15, Section 4.1)

$n = 0.213 C_n \tau_o^{-0.4} = 0.213(0.238)(0.61)^{-0.4} = 0.062$

The discharge is calculated from Manning's equation (Refer to FDM 13-30-10, Equation 1):

$$Q = \frac{1.49}{n} A R^{2/3} S_0^{1/2} = 1.49/0.062(4.00)(0.485)^{2/3}(0.02)^{1/2} = 8.4\ ft^3/s$$

Step 4. Since this calculated flow value is more than 2 percent different from the design flow, repeat step 2 with a new, estimated flow depth.

Step 2 (2nd iteration). Estimate a new depth more than the initial estimate as the calculated Q < given Q

d = 1.21 ft, and calculate the new geometric channel properties:

$A = Bd + Zd^2 = 0.0(1.21) + 4(1.21)^2 = 5.86\ ft^2$

$P = B + 2d\ (Z^2 + 1)^{1/2} = 0.0 + 2(1.21)\ (4^2 + 1)^{1/2} = 9.98$ ft

R = A/P = (5.86)/(9.98) = 0.587 ft

Step 3 (2nd iteration). To estimate n, determine the applied shear stress on the grass lining and the discharge:

$\tau_o = \gamma R S_o = 62.4(0.587)(0.02) = 0.73$ lb / ft (Refer to FDM 13-30-10, Equation 2)

Determine Manning's n from FDM 13-30-15, Equation 12:

$C_n = 0.237(C_s)^{0.1}(h)^{0.528} = 0.237(9.0)^{0.1}(0.67)^{0.528} = 0.238$ (HEC-15, Section 4.1)

$n = 0.213 C_n \tau_o^{-0.4} = 0.213(0.238)(0.73)^{-0.4} = 0.057$

The discharge is calculated from Manning's equation:

$$Q = \frac{1.49}{n} AR^{2/3} S_0^{1/2} = 1.49/0.057(5.86)(0.587)^{2/3}(0.02)^{1/2} = 15.2 \text{ ft}^3/\text{s}$$

Step 4 (2nd iteration) Since this value is within 2 percent of the design flow, proceed to step 5.

Step 5. The maximum shear on the channel bottom is.

$$\tau_d = \gamma d S_o = 62.4(1.21)(0.02) = 1.51 \text{ lb/ft}^2$$

The permissible soil shear stress is given by Equation 4.6., HEC-15 Section 4.3.3.2

$$\tau_{p,soil} = (c_1 PI^2 + c_2 PI + c_3)(c_4 + c_5 e)^2 c_6 = (1.07(16)^2 + 14.3(16) + 47.7)(1.42 - 0.61(0.35))^2(0.00010) = 0.08 \text{ lb/ft}^2$$

Equation 2 gives the permissible shear stress on the vegetation. The value of C_f is found in Table 4.5, HEC-15 Section 4.3.1. The soil grain roughness, n_s, equals 0.016 unless the D_{75} of the soil is greater than 0.05 in.

$$\tau_p = \frac{\tau_{p,soil}}{(1 - C_f)}\left(\frac{n}{n_s}\right)^2 = (0.08/(1\text{-}0.9))(0.057/0.016)^2 = 10.2 \text{ lb/ft}^2$$

The safety factor for this channel is taken as 1.0. (Refer to FDM 13-30-10, General Design Procedures)

Step 6. The grass lining is acceptable since the maximum shear on the vegetation (1.51 lb/ft^2) is less than the permissible shear of 10.2 lb/ft^2.

Grass Lined Channel Design WisDOT Spreadsheet Worksheet

Download a zipped working copy of the spreadsheets at:

http://wisconsindot.gov/rdwy/fdm/files/WisDOT-Stormwater-Drainage-WQ-Channel-Spreadsheets.zip

1	**Lining Type: Vegetation**								
2	**Project ID:**								
3	**Location:**								
4	**Designer/Checker:**								
5	**Date:**								
6									
7	**STA**	**10+00**	**10+00**	**12+00**	**13+00**	**14+00**	**15+00**	**16+00**	**17+00**
8	**Left, Center or Right**	**R**	**R**	**R**	**R**	**R**	**R**	**R**	**R**
9	***Channel/Ditch Geometry***								
10	Channel Slope, S_o (ft/ft)	**0.02**	**0.02**						
11	Channel Bottom Width, B (ft)	**0**	**0**						
12	Channel Side Slope, z_1	**4**	**4**						
13	Channel Side Slope, z_2	**4**	**4**						
14	Flow Depth, d (ft) Solve iteratively	**1.00**	**1.21**						
15	Safety Factor, SF	**1.0**	**1.0**						
16	***Vegetation/Soil Parameters***								
17	Vegetation Retardance Class	**C**	**C**						
18	Vegetation Condition	**good**	**good**						
19	Vegetation Growth Form	**turf**	**turf**						
20	Soil Type	**cohesive**	**cohesive**						
21	D_{75} (in) (Set at 0.00 for cohesive soils)								
22	ASTM Soil Class	**SC**	**SC**						
23	Plasticity Index, PI	**16**	**16**						
24	***Results Summary***								
25	Design Q (ft^3/s)	**15.0**	**15.0**						
26	Calculated Q (ft^3/s)	8.4	15.2	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
27	Difference Between Design & Calc. Flow (%)	-44.0%	1.2%	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
28	**Stable (Yes or No)**	**YES**	**YES**	**#VALUE!**	**#VALUE!**	**#VALUE!**	**#VALUE!**	**#VALUE!**	**#VALUE!**
29	***Channel Parameters***								
30	Vegetation Height, h (ft)	0.67	0.67	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
31	Grass Roughness Coefficient, C_n	0.238	0.238	undefined	undefined	undefined	undefined	undefined	undefined
32	Cover Factor, C_f	0.90	0.90	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
33	Noncohesive Soil								
34	Soil Grain Roughness, n_s	0.016	0.016	0.016	0.016	0.016	0.016	0.016	0.016
35	Permissible Soil Shear Stress, τ_p (lb/ft^2)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
36	Cohesive Soil								
37	Porosity, e	0.35	0.35	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
38	Soil Coefficient 1, c_1	1.0700	1.0700	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
39	Soil Coefficient 2, c_2	14.30	14.30	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
40	Soil Coefficient 3, c_3	47.700	47.700	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
41	Soil Coefficient 4, c_4	1.42	1.42	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
42	Soil Coefficient 5, c_5	-0.61	-0.61	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
43	Soil Coefficient 6, c_6	0.00010	0.00010	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE
44	Permissible Soil Shear Stress, τ_p (lb/ft^2)	0.080	0.080	N/A	N/A	N/A	N/A	N/A	N/A
45	Total Permissible Shear Stress, τ_p (lb/ft^2)	0.080	0.080	0.000	0.000	0.000	0.000	0.000	0.000
46	Cross Sectional Area, A (ft^2)	4.000	5.856	0.000	0.000	0.000	0.000	0.000	0.000
47	Wetted Perimeter, P (ft)	8.25	9.98	0.00	0.00	0.00	0.00	0.00	0.00
48	Hydraulic Radius, R (ft)	0.485	0.587	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
49	Top Width, T (ft)	8.00	9.68	0.00	0.00	0.00	0.00	0.00	0.00
50	Hydraulic Depth, D (ft)	0.500	0.605	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
51	Froude Number (Q design)	0.523	0.587	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
52	Channel Shear Stress, τ_p (lb/ft^2)	0.61	0.73	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
53	Actual Sheer Stress, τ_d (lb/ft^2)	1.25	1.51	0.00	0.00	0.00	0.00	0.00	0.00
54	Mannings n	0.062	0.057	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
55	Average Velocity, V (ft/s)	3.75	2.56	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
56	Calculated Flow, Q (ft^3/s)	8.4	15.2	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
57	Difference Between Design & Calc. Flow (%)	-44.0%	1.2%	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
58	Effective Shear on Soil Surface, τ_e (lb/ft^2)	0.008	0.012	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
59	Total Permissible Shear on Veg., $\tau_{p,veg}$ (lb/ft^2)	12.03	10.17	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!
60	Stable (Y or N)	YES	YES	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!	#VALUE!

GRASS LINED CHANNEL DESIGN EXAMPLE (USING WisDOT SPREADSHEET)

To use this spreadsheet, enter data into all the grey cells. The spreadsheet is designed so that you can select the cells in column C from rows 5 to 52 and drag them across to create additional columns for additional swale segments.

Enter the following information into the spreadsheet, as shown in the example to the right. Note that many of the variables are selected using a drop-down list box. In Figures 1 to 3, the first data column represents values from the first iteration of the above example, and the second column displays values from the second iteration of the above example.

Lines 2 – 5: Enter the project information as described.

Lines 7 – 8: For each channel segment, enter the highway station and whether the channel is on the left, center or right (L, C or R) of the highway.

Line 10: Enter the channel bottom slope, S_o, (ft/ft).

Line 11: Enter the channel bottom width, B, (ft).

1	**Lining Type: Vegetation**		
2	**Project ID:**		
3	**Location:**		
4	**Designer/Checker:**		
5	**Date:**		
6			
7	**STA**	**10+00**	**10+00**
8	**Left, Center or Right**	**R**	**R**
9	***Channel/Ditch Geometry***		
10	Channel Slope, S_o (ft/ft)	**0.02**	**0.02**
11	Channel Bottom Width, B (ft)	**0**	**0**
12	Channel Side Slope, z_1	**4**	**4**
13	Channel Side Slope, z_2	**4**	**4**
14	Flow Depth, d (ft) Solve iteratively	**1.00**	**1.21**
15	Safety Factor, SF	**1.0**	**1.0**
16	***Vegetation/Soil Parameters***		
17	Vegetation Retardance Class	**C**	**C**
18	Vegetation Condition	**good**	**good**
19	Vegetation Growth Form	**turf**	**turf**
20	Soil Type	**cohesive**	**cohesive**
21	D_{75} (in) (Set at 0.00 for cohesive soils)		
22	ASTM Soil Class	**SC**	**SC**
23	Plasticity Index, PI	**16**	**16**

Figure 15.1 Grass Lined Channel Design Spreadsheet Data Entry Section

Lines 12-13: Enter the side slopes of the channel (z_1,z_2) (z Horizontal: 1 Vertical)

Line 14: Enter the initial estimate of the water depth, d, in the swale (ft).

Line 15: SF, the selected safety factor.

Line 17: Vegetation Retardance Class (A, B, C, D, or E) selected from a drop-down menu.

Line 18: Vegetation condition (good, fair or poor), selected from a drop-down menu

Line 19: Vegetation growth form (bunched, mixed or turf), selected from a drop-down menu. Select “bunched” for seed mixes 70, 70A, 75 and 80.

Line 20: Soil Type (cohesive or non-cohesive) of the soil you are constructing the swale on, selected from a drop-down menu.

Line 21: If non-cohesive, enter the D_{75} of the soil. Typical values are listed on Table 2. Set this value to zero for cohesive soils.

Line 22: If cohesive, enter ASTM Soil Class (CH, CL, GC, GM, MH, ML, SC, SM) of the soil, selected from a drop-down menu.

Line 23: If cohesive, enter the PI (Plasticity Index) of the soil. This value can be obtained from the soils engineer or from the NRCS website: http://websoilsurvey.nrcs.usda.gov/app/ and begin by pressing the ‘Start WSS’ button. To determine the PI:

1. Draw an outline around the geographic area of interest (AOI) of your project.
2. Select the ‘Soil Data Explorer’ tab.
3. Select the ‘Soil Properties and Qualities’ tab.

4. Select 'Plasticity Index' from the 'Soil Physical Properties' menu.
5. Select the 'Layer Option' you want and enter a depth range, if appropriate.
6. Press the 'View Rating' button to view the plasticity index of your area of interest. Use the value in the Ratings (percent) column of the Plasticity Index Table for the PI value of the soil types in your AOI.

Grass Lined Channel Design Results Summary

24	***Results Summary***		
25	Design Q (ft^3/s)	**15.0**	**15.0**
26	Calculated Q (ft^3/s)	8.4	15.2
27	Difference Between Design & Calc. Flow (%)	-44.0%	1.2%
28	**Stable (Yes or No)**	**YES**	**YES**

Figure 15.2 Grass Lined Channel Design Spreadsheet Results Summary Section

Line 25: Enter the design flow for the channel section, in ft^3/s.

Line 26: The calculated flow for the channel, based upon the depth of flow you entered, the channel geometry, and the grass swale parameters.

Line 27: The percent difference between the design flow and the calculated flow.

Line 28: Channel bottom lining stability status (Yes or No).

Analysis Process:

Once you have entered all relevant information, you must change the channel depth, d, in Line 13 until the difference in the Design Q and the Calculated Q is less than 2%. The spreadsheet will indicate, in Line 27, whether the grass lined channel is stable or unstable.

If the channel is unstable, you have the following options:

1. Flatten the longitudinal slope by either modifying the slope grade or putting in permanent ditch checks that are not in the clear zone. If you use properly spaced permanent ditch checks, assume a longitudinal slope of 1%. Ditch checks should be spaced such that the base of the upstream check is at the same elevation as the top of the downstream check
2. Flatten the side slopes and/or widen the ditch bottom to decrease the flow depth
3. Select a different liner, such as a TRM (Turf Reinforcement Mat) or riprap

Grass Lined Channel Spreadsheet Intermediate Calculations

The intermediate calculations are values determined by the spreadsheet, based upon the procedures described in HEC-15. The user does not enter any of these values into the spreadsheet.

29	**Channel Parameters**		
30	Vegetation Height, h (ft)	0.67	0.67
31	Grass Roughness Coefficient, C_n	0.238	0.238
32	Cover Factor, C_f	0.90	0.90
33	Noncohesive Soil		
34	Soil Grain Roughness, n_s	0.016	0.016
35	Permissible Soil Shear Stress, τ_p (lb/ft^2)	N/A	N/A
36	Cohesive Soil		
37	Porosity, e	0.35	0.35
38	Soil Coefficient 1, c_1	1.0700	1.0700
39	Soil Coefficient 2, c_2	14.30	14.30
40	Soil Coefficient 3, c_3	47.700	47.700
41	Soil Coefficient 4, c_4	1.42	1.42
42	Soil Coefficient 5, c_5	-0.61	-0.61
43	Soil Coefficient 6, c_6	0.00010	0.00010
44	Permissible Soil Shear Stress, τ_p (lb/ft^2)	0.080	0.080
45	Total Permissible Shear Stress, τ_p (lb/ft^2)	0.080	0.080
46	Cross Sectional Area, A (ft^2)	4.000	5.856
47	Wetted Perimeter, P (ft)	8.25	9.98
48	Hydraulic Radius, R (ft)	0.485	0.587
49	Top Width, T (ft)	8.00	9.68
50	Hydraulic Depth, D (ft)	0.500	0.605
51	Froude Number (Q design)	0.523	0.587
52	Channel Shear Stress, τ_o (lb/ft^2)	0.61	0.73
53	Actual Sheer Stress, τ_d (lb/ft^2)	1.25	1.51
54	Mannings n	0.062	0.057
55	Average Velocity, V (ft/s)	3.75	2.56
56	Calculated Flow, Q (ft^3/s)	8.4	15.2
57	Difference Between Design & Calc. Flow (%)	-44.0%	1.2%
58	Effective Shear on Soil Surface, τ_e (lb/ft^2)	0.008	0.012
59	Total Permissible Shear on Veg., $\tau_{p,veg}$ (lb/ft^2)	12.03	10.17
60	Stable (Y or N)	YES	YES

Figure 15.3 Channel Parameters Section Spreadsheet Data

Channel Parameters:

Line 30: The vegetation height, from Table 1 in this procedure and from HEC-15 Table 4-1.

Line 31: The grass roughness coefficient, from HEC-15, Equation 4.1.

Line 32: The cover factor, from HEC-15, Table 4-5.

Lines 34 - 35: Calculations, described in HEC-15, to determine the permissible soil shear stress for noncohesive (or sandy) soils.

Line 37 - 45: Calculations and coefficients, described in HEC-15, to determine the permissible soil shear stress for cohesive soils.

Line 46: The cross section area, based upon the depth of flow (line 14) and channel geometry.

Line 47: The wetted perimeter, based upon the depth of flow (line 14) and channel geometry.

Lines 48: The hydraulic radius, based upon the depth of flow (line 14) and channel geometry.

Line 48: The top width, based upon the depth of flow (line 14) and channel geometry.

Line 50: The hydraulic depth, which is the area (line 45) divided by the top width (line 48).

Line 51: The Froude number, which is a function of the calculated flow, the cross sectional area, the gravitational constant, g, and the hydraulic depth.

Line 52: The channel shear stress, which is a function of the hydraulic radius (line 47), the channel slope (line 9), and the density of water. This value is used to calculate Manning's n.

Line 53: The actual shear stress, which is a function of the flow depth (line 13), the channel slope (line 9), and the density of water. This value is used to determine the effective shear on the soil, and thus the stability of the channel.

Line 54: The Manning's n value selected by the spreadsheet, which is determined in the Manning's n spreadsheet section below.

Line 55: The average velocity, which is found by dividing the calculated flow (line 25) by the cross section area (line 45).

Line 56: The calculated flow, which is calculated using Manning's equation.

Line 57: The percent difference in flow between the calculated flow and the design flow.

Line 58: The effective shear stress of the grass lining, which is due to the shear force dissipation due to the grass stems and the grass plant stabilization (both root and stem) against turbulent fluctuations.

Line 59: Total permissible shear of the vegetative lining, which includes the combined effects of the soil permissible shear stress and the effective shear stress transferred through the vegetative lining.

Line 60: The channel is stable if the permissible shear stress (line 58) is greater than the effective shear stress (line 52) times the safety factor (line 14).

DESIGN EXAMPLE (USING EQUATIONS): RIPRAP CHANNEL (MILD SLOPE)

Design a riprap lining for a trapezoidal channel.

Given:

$Q = 40$ ft^3/s

$B = 0.0$ ft (bottom width)

$Z = 4$

$S_o = 0.02$ ft/ft

Solution:

Step 1. Channel characteristics and design discharge are given above.

Step 2. The WisDOT standard riprap sizes are listed in Table 25.1. Assume that γ_s =165 lb/ft3 for all classes. Try light riprap for the initial trial. D50 = 0.83 ft

Step 3. Assume an initial trial depth, di, of 1.5 ft. Using the geometric properties of a trapezoid, the maximum and average flow depths are found:

$A = Bd+Zd^2 = 0.0(2)+4(2)^2 = 16.0$ ft2

$P = B + 2d\sqrt{Z^2+1} = 0 + 2(2)\sqrt{4^2+1} = 16.5$ ft (wetted perimeter)

$R = A/P = 16.0/16.5 = 0.97$ ft (hydraulic radius)

$T = B+2dZ = 0.0+2(2)(4) = 16.0$ ft

$d_a = A/T = 16.00/16.0 = 1.00$ ft

Step 4. The relative depth ratio, $d_a/D_{50} = 1.0/0.83 = 1.20$. Therefore, use Equation 15 to calculate Manning's n.

$$b = 1.14\left(\frac{D_{50}}{T}\right)^{0.453}\left(\frac{d_a}{D_{50}}\right)^{0.814} = 1.14\left(\frac{0.83}{16.0}\right)^{0.453}\left(\frac{1.00}{0.83}\right)^{0.814} = 0.347$$

$$f(Fr) = \left(\frac{0.28Fr}{b}\right)^{\log(0.755/b)} = \left(\frac{0.28\left(40/\left(16\sqrt{32.2(1)}\right)\right)}{0.347}\right)^{\log(0.755/0.347)} = 0.705$$

$$f(REG) = 13.434\left(\frac{T}{D_{50}}\right)^{0.492} b^{1.025(T/D_{50})^{0.118}} = 13.434\left(\frac{16.0}{0.83}\right)^{0.492} 0.347^{1.025(16.0/0.83)^{0.118}} = 12.4$$

$$f(CG) = \left(\frac{T}{d_a}\right)^{-b} = \left(\frac{16.0}{1.0}\right)^{-0.347} = 0.382$$

$$n = \frac{1.49d_a^{1/6}}{\sqrt{g}f(Fr)f(REG)f(CG)} = \frac{1.49(1.00)^{1/6}}{\sqrt{32.2}(0.705)(12.4)(0.382)} = 0.079$$

Calculate Q_i using Manning's equation:

$$Q_i = \frac{1.49}{n}AR^{2/3}S^{1/2} = \frac{1.49}{0.079}(16.0)(0.97)^{2/3}(0.02)^{1/2} = 4 \text{ ft}^3/\text{s}$$

Step 5. Since this estimate is more than 2 percent from the design discharge, estimate a new depth in step 3.

Step 3 (2nd iteration). Estimate a new depth:

$$d_{i+1} = d_i\left(\frac{Q}{Q_i}\right)^{0.4} = 2.0\left(\frac{40}{41.8}\right)^{0.4} = 1.96 \quad \text{ft}$$

Using the geometric properties of a trapezoid, the maximum and average flow depths are found:

$A = Bd+Zd^2 = 0.0(2)+4(1.96)^2 = 15.37\ ft^2$

$P = B + 2d\sqrt{Z^2+1} = 0 + 2(1.96)\sqrt{4^2+1} = 16.16$ ft

$R = A/P = 15.37/16.16 = 0.951$ ft

$T = B+2dZ = 0.0+2(1.96)(4) = 15.7$ ft

$d_a = A/T = 15.37/15.7 = 0.98$ ft

Step 4. (2nd iteration)

$$b = 1.14\left(\frac{D_{50}}{T}\right)^{0.453}\left(\frac{d_a}{D_{50}}\right)^{0.814} = 1.14\left(\frac{0.83}{15.7}\right)^{0.453}\left(\frac{0.98}{0.83}\right)^{0.814} = 0.345$$

$$f(Fr) = \left(\frac{0.28Fr}{b}\right)^{\log(0.755/b)} = \left(\frac{0.28\left(40/\left(16\sqrt{32.2(0.98)}\right)\right)}{0.345}\right)^{\log(0.755/0.345)} = 0.717$$

$$f(REG) = 13.434\left(\frac{T}{D_{50}}\right)^{0.492} b^{1.025(T/D_{50})^{0.118}} = 13.434\left(\frac{15.7}{0.83}\right)^{0.492} 0.345^{1.025(15.7/0.83)^{0.118}} = 12.2$$

$$f(CG) = \left(\frac{T}{d_a}\right)^{-b} = \left(\frac{15.7}{0.98}\right)^{-0.345} = 0.385$$

$$n = \frac{1.49 d_a^{1/6}}{\sqrt{g}\,f(Fr)f(REG)f(CG)} = \frac{1.49(0.98)^{1/6}}{\sqrt{32.2}(0.717)(12.2)(0.385)} = 0.078$$

Calculate Q_{i+1} using Manning's equation:

$$Q_{i+1} = \frac{1.49}{n} A R^{2/3} S^{1/2} = \frac{1.49}{0.078}(15.37)(0.951)^{2/3}(0.02)^{1/2} = 40.1 \quad ft^3/s$$

Step 5 (2nd (iteration). Since this estimate is within 2 percent of the design discharge, proceed to step 6 with the most recently calculated depth.

Step 6. Need to calculate the shear velocity and Reynolds number, Re, to determine Shields' parameter, F*, and SF. Calculate the shear velocity, V*, and the Reynolds number to determine the Shield's parameter and the safety factor, SF.

$$V^* = \sqrt{gdS} = \sqrt{(32.2)(1.96)(0.02)} = 1.12$$

Reynolds $R_e = \frac{V^* D_{50}}{\upsilon} = \frac{1.12(0.83)}{1.127x10^{-5}} = 7.64x10^4$ number,

Since the Reynolds number is between $4x10^4$ and $2x10^5$, the F* value and the SF are interpolated, as described in FDM 13-30-25, Table 25.2, to get:

F* = 0.071

SF = 1.12

Since channel slope is less than 5 percent, use Equation 8 to calculate minimum stable D_{50}.

$$D_{50} \geq \frac{SFdS_{\circ}}{F^{*}(SG-1)} = \frac{(1.12)(1.96)(0.02)}{(0.071)(2.65-1)} = 0.4 \text{ ft}$$

Since the D_{50} calculated in step 6 is less than or equal to the trial riprap size of 0.83 ft, which is WisDOT light riprap, then the trial size is acceptable.

As was described by Equation 5 in FDM 13-30-10, the shear stress on the channel side is less than the maximum shear stress occurring on the channel bottom. However, since gravel and riprap linings are noncohesive, as the angle of the side slope approaches the angle of repose (Attachment 25.5) of the channel lining, the lining material becomes less stable. The stability of a side slope lining is a function of the channel side slope and the angle of repose of the riprap. This essentially results in a lower permissible shear stress on the side slope than on the channel bottom. These two counterbalancing effects lead to the design equation described in HEC-15 Section 6.3.2 for specifying a riprap size for the side slope given the riprap size required for a stable channel bottom.

Channels lined with gravel or riprap on side slopes steeper than 3:1 (H:V) may become unstable and should be avoided where feasible. If steeper side slopes are required, they should be assessed using both Equation 6.11 (HEC-15) and Equation 6.8 (HEC-15) in conjunction with Equation 6.15 (HEC-15). Use the larger of the two riprap sizes for the design.

Note that the increased shear stresses created by flow around a bend may produce scour that would not occur in straight channel reaches. To prevent bend scour, it may be necessary to increase the rock riprap size or use a different lining material in the bend. Refer to the section on bend stability for more guidance (FDM 13-30-10).

Riprap Channel (Mild Slope) WisDOT Spreadsheet Worksheet

Download a zipped working copy of the WisDOT Rock Channel Lining spreadsheet from the link at the top of FDM 11-30 Attachment 15.2.

1	**Lining Type: Riprap**								
2	**Project ID:**								
3	**Location:**								
4	**Designer/Checker:**								
5	**Date:**								
6									
7	**STA**	**10+00**	**11+00**	**12+00**	**13+00**	**14+00**	**15+00**	**16+00**	**17+00**
8	**Left, Center, or Right**	**R**	**R**	**R**	**R**	**R**	**R**	**R**	**R**
9	***Channel Geometry***								
10	Channel Slope, S_o (ft/ft)	0.02							
11	Channel Bottom Width, B (ft)	0							
12	Channel Side Slope, z_1	4							
13	Channel Side Slope, z_2	4							
14	Curvature Radius, R_c (ft)	50							
15	Depth of Flow, d (ft) Solve iteratively	2.00							
16	***Riprap Parameters***								
17	Median Riprap Size, D_{50} (ft)	1.04							
18	Riprap Specific Weight, γ_s (lb/ft^3)	165							
19	Riprap Angle of Repose, ϕ , (degrees)	41.8							
20	Safety Factor, SF	1.20							
21	Safety Factor, SF (used in calculation)	1.20	1.00	1.00	1.00	1.00	1.00	1.00	1.00
22	***Results Summary***								
23	Design Flow, Q (ft^3/s)	40							
24	Calculated Flow, Q (cfs)	37.5	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
25	Difference Between Design & Calc. Flow (%)	-6.1%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
26	**Bottom Lining Stable (Yes or No)**	Yes	No	No	No	No	No	No	No
27	**Side Lining Stable (Yes or No)**	Yes	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
28	**Bottom in Bend Stable (Yes or No)**	Yes	N/A	N/A	N/A	N/A	N/A	N/A	N/A
29	**Side in Bend Stable (Yes or No)**	Yes	N/A	N/A	N/A	N/A	N/A	N/A	N/A
30	**Downstream Length of Protection (ft)**	7	N/A	N/A	N/A	N/A	N/A	N/A	N/A
31	**Additional Freeboard Required, (ft)**	0.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
32	***Channel Parameters***								
33	Cross Sectional Area, A (ft^2)	16.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34	Top Width, T (ft)	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
35	Average Depth, d_a (ft)	1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
36	Wetted Perimeter, P (ft)	16.49	0.00	0.00	0.00	0.00	0.00	0.00	0.00
37	Hydraulic Radius, R (ft)	0.970	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
38	Depth to D_{50} Ratio, d_a/D_{50}	1.0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
39	Mannings n	0.088	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
40	Average Velocity, V (ft/s)	2.35	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
41	Calculated Flow, Q (ft^3/s)	37.5	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
42	Difference Between Design & Calc. Flow (%)	-6%	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
43	Suggested Trial Depth, d_{i+1} (ft)	2.051	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
44	***Manning's n***								
45	Manning's n (Blodgett)	0.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
46	Manning's n (Bathurst)	0.088	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
47	Effective Roughness Concentration, b	0.320	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
48	Froude Number, Fr (design Q)	0.441	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
49	Froude Number function, f(Fr)	0.701	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
50	Roughness Element Geometry, f(REG)	10.3	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
51	Channel Geometry Function, f(CG	0.412	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
52	***Bottom Shear***								
53	Shear Velocity, V_* (ft/s)	1.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
54	Reynolds Number, R_e	9.7E+04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
55	Shield's Parameter, F*	0.084	0.047	0.047	0.047	0.047	0.047	0.047	0.047
56	Safety Factor, SF	1.18	1.00	1.00	1.00	1.00	1.00	1.00	1.00
57	Maximum Shear Stress, τ_d (lb/ft^2)	2.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
58	Permissible Shear Stress, S_o<=10%, τ_p (lb/ft^2)	9.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
59	Stability Number, η	0.26	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
60	Steepest Channel Side Slope, z	4	0	0	0	0	0	0	0
61	Channel Side Slope Angle, θ (radians)	0.24	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
62	Channel Bottom Slope Angle, α (radians)	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00
63	Riprap Angle of Repose, ϕ , (radians)	0.730	0.000	0.000	0.000	0.000	0.000	0.000	0.000
64	Weight Vector Angle, B (radians)	0.44	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
65	Channel Geometry and Riprap Size Func Δ	0.99	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
66	Permissible Shear Stress, S_o>=5%, τ_p (lb/ft^2)	9.0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
67	Permissible Shear based on Slope, τ_p (lb/ft^2)	9.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
68	Adjusted Permissible Shear, τ_p/SF (lb/ft^2)	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
69	Bottom Lining Stable (Yes or No)	Yes	**No**	**No**	**No**	**No**	**No**	**No**	**No**
70	Stable D_{50} (ft)	0.35	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
71	***Side Shear***								
72	Channel Side to Bottom Shear Stress Ratio, K_1	0.93	0.77	0.77	0.77	0.77	0.77	0.77	0.77
73	Channel Side Shear Stress, τ_s (lb/ft^2)	2.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00
74	Side Slope Angle, θ (radians)	0.245	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
75	Side Slope Angle, θ (degrees)	14.0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
76	Tractive Force Ratio, K_2	0.93	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
77	Permissible Side Tractive Force, τ_{ps} (lb/ft^2)	8.34	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
78	Side Lining Stable (Yes or No)	Yes	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
79	Stable D_{50} (ft)	0.35	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
80	***Bend Shear***								
81	Curvature Radius, R_c (ft)	50	0	0	0	0	0	0	0
82	Ratio of Radius of Curvature to Top Width, R_c/T	3.13	N/A	N/A	N/A	N/A	N/A	N/A	N/A
83	f(Channel Bend and Bottom Shear Stress), K_b	1.81	N/A	N/A	N/A	N/A	N/A	N/A	N/A
84	Shear Stress on the Channel Bottom, τ_b (lb/ft^2)	4.51	N/A	N/A	N/A	N/A	N/A	N/A	N/A
85	Bottom in Bend Stable (Yes or No)	Yes	N/A	N/A	N/A	N/A	N/A	N/A	N/A
86	Shear Stress on the Channel Side, τ_{bs} (lb/ft^2)	4.19	N/A	N/A	N/A	N/A	N/A	N/A	N/A
87	Side in Bend Stable (Yes or No)	Yes	N/A	N/A	N/A	N/A	N/A	N/A	N/A
88	Downstream Length of Protection, L_p (ft)	7	N/A	N/A	N/A	N/A	N/A	N/A	N/A
89	Addition Freeboard Required, Δd (ft)	0.1	N/A	N/A	N/A	N/A	N/A	N/A	N/A

<u>Instructions and Example Riprap Lined Design Example for Channel Slopes ≤ 20% Using the WisDOT Spreadsheet</u>

WisDOT has prepared a spreadsheet that incorporates all the design guidelines and equations described in HEC-15 to design rock lined channels. The spreadsheet is divided into three sections:

1. a data entry section,
2. a results section, and
3. an intermediate calculations section.

Each of these sections is described within the line-by-line instructions below.

Riprap Spreadsheet Data Entry, Slopes ≤ 20%:

Enter data to analyze channel sections in the grey or blue cells of the spreadsheet, as described below.

Lines 2 - 5: Enter the project information as described.

Lines 7 - 8: For each channel segment, enter the highway station and whether the channel is on the left, center, or right (L, C or R) of the highway.

Line 10: Enter the channel bottom slope (ft/ft).

Line 11: Enter the channel bottom width, B (ft).

Lines 12-13: Enter the side slopes of the channel (z Horizontal: 1 Vertical)

1	**Lining Type: Riprap**		
2	**Project ID:**		
3	**Location:**		
4	**Designer/Checker:**		
5	**Date:**		
6			
7	**STA**	**10+00**	**10+00**
8	**Left, Center, or Right**	**R**	**R**
9	***Channel Geometry***		
10	Channel Slope, S_o (ft/ft)	0.02	0.02
11	Channel Bottom Width, B (ft)	0	0
12	Channel Side Slope, z_1	4	4
13	Channel Side Slope, z_2	4	4
14	Curvature Radius, R_c (ft)	50	50
15	Depth of Flow, d (ft) Solve iteratively	2.00	1.96
16	***Riprap Parameters***		
17	Median Riprap Size, D_{50} (ft)	1.04	0.83
18	Riprap Specific Weight, γ_s (lb/ft^3)	165	165
19	Riprap Angle of Repose, ϕ , (degrees)	41.8	41.8
20	Safety Factor, SF	1.20	1.20
21	Safety Factor, SF (used in calculation)	1.20	1.20

Figure 25.1 Riprap Lined Channel Design Spreadsheet Data Entry Section

Line 14: Enter the radius of curvature of the bend R_c, if there is one, to the channel centerline (ft).

Line 15: Your initial estimate of the water depth in the channel, d (ft).

Line 17: D_{50}, your initial estimate of the median size of the riprap (ft). Start with the smallest reasonable riprap size to prevent riprap over sizing. Use the drop-down menu to select the standard WisDOT riprap size you want to analyze.

Line 18: The specific weight of the rock, γ_s, (lbs/ft^3).

Line 19: The angle of repose for the rock (degrees). Find this value from Figure 8, Angle of Repose of Riprap in Terms of Mean Size and Shape of Stone.

Line 20: SF, the safety factor you select to design the channel. The spreadsheet will also calculate a safety factor, and then use whichever value is higher (Line 21).

Riprap Spreadsheet Results Summary, Slopes ≤ 20%:

22	**Results Summary**		
23	Design Flow, Q (ft^3/s)	40	40
24	Calculated Flow, Q (cfs)	37.5	40.1
25	Difference Between Design & Calc. Flow (%)	-6.1%	0.3%
26	**Bottom Lining Stable (Yes or No)**	Yes	Yes
27	**Side Lining Stable (Yes or No)**	Yes	Yes
28	**Bottom in Bend Stable (Yes or No)**	Yes	Yes
29	**Side in Bend Stable (Yes or No)**	Yes	Yes
30	**Downstream Length of Protection (ft)**	7	7
31	**Additional Freeboard Required, (ft)**	0.1	0.1

Figure 25.2 Riprap Lined Channel Design Spreadsheet Data Entry Section

Line 23 Enter the design flow for the channel section (ft^3/s).

Line 24 The calculated flow for the channel, based upon the depth of flow you entered, the channel geometry, and the riprap parameters.

Line 25: The percent difference between the design flow and the calculated flow.

Line 26: Channel bottom lining stability status (Yes or No).

Line 27: Channel side lining stability status (Yes or No).

Line 28: Channel bottom lining stability status for channel bend sections (Yes, No or N/A if the section is a straight section).

Line 29: Channel side lining stability status for channel bend sections (Yes, No or N/A if the section is a straight section).

Line 30: The length of channel downstream of a bend that requires protection, in feet. (N/A if the section is a straight section)

Line 31: Additional freeboard required due to elevated flows in a channel bend, in feet. (N/A if the section is a straight section)

Analysis Process:

Once you have entered all the relevant information, you must change the channel depth, d, in Line 14 until the difference in the Design Q (line 22), which you must enter, and the Calculated Q (line 23), is less than 2%. The spreadsheet will indicate whether the riprap lined channel is stable or unstable for straight channels (bottom and sides) and channel bend bottom and sides. If it is unstable, you have the following options:

1. Flatten the longitudinal slope by either modifying the slope grade or putting in permanent ditch checks that are not in the clear zone. If you use properly spaced permanent ditch checks, assume a longitudinal slope of 1%. Ditch checks should be spaced such that the base of the upstream check is at the same elevation as the top of the downstream check
2. Flatten the side slopes and/or widen the ditch bottom to decrease the flow depth
3. Select a different riprap size.

Riprap Spreadsheet Intermediate Calculations, Slopes ≤ 20%:

To determine the stability of a riprap channel liner, the spreadsheet makes a number of calculations, based upon Chapter 6 of HEC-15, related to channel geometry, Manning's n, bottom shear, side shear and bend shear. Each of these types of calculations is described below. For a complete description, review Chapters 3 and 6 of HEC-15.

Channel Parameters:

32	***Channel Parameters***		
33	Cross Sectional Area, A (ft^2)	16.00	15.37
34	Top Width, T (ft)	16.0	15.7
35	Average Depth, d_a (ft)	1.000	0.980
36	Wetted Perimeter, P (ft)	16.49	16.16
37	Hydraulic Radius, R (ft)	0.970	0.951
38	Depth to D_{50} Ratio, d_a/D_{50}	1.0	1.2
39	Mannings n	0.088	0.078
40	Average Velocity, V (ft/s)	2.35	2.61
41	Calculated Flow, Q (ft^3/s)	37.5	40.1
42	Difference Between Design & Calc. Flow (%)	-6%	0%
43	Suggested Trial Depth, d_{i+1} (ft)	2.051	1.957

Figure 25.3 Riprap Lined Channel Design Spreadsheet Data Channel Parameter Section

Line 33: The cross section area, A, based upon the depth of flow (line 14) and channel geometry.

Line 34: The top width, T, based upon the depth of flow (line 15) and channel geometry.

Line 35: The average depth, d_a, which is the area (line 33) divided by the top width (line 34).

Line 36: The wetted perimeter, P, based upon the depth of flow (line 15) and channel geometry.

Line 37: The hydraulic radius, R, based upon the depth of flow (line 15) and channel geometry.

Line 38: The ratio of average depth to riprap D_{50}, used to determine which Manning's n equation is appropriate for the channel.

Line 39: The Manning's n value selected by the spreadsheet, which is determined in the Manning's n spreadsheet section below.

Line 40: The average velocity, which is calculated using Manning's equation.

Line 41: The calculated flow, which is the product of the velocity (line 40) and area (line 33).

Line 42: The percent difference in flow between the calculated flow and the design flow.

Line 43: The suggested trial depth, d_{i+1}, to aid in the iterative solution process. The user can enter this value into line 15, or just enter his or her best guesses of the depth until the calculated and design flows are within 2% of each other.

Manning's n:

44	***Manning's n***		
45	Manning's n (Blodgett)	0.000	0.000
46	Manning's n (Bathurst)	0.088	0.078
47	Effective Roughness Concentration, b	0.320	0.345
48	Froude Number, Fr (design Q)	0.441	0.463
49	Froude Number function, f(Fr)	0.701	0.717
50	Roughness Element Geometry, f(REG)	10.3	12.2
51	Channel Geometry Function, f(CG)	0.412	0.385

Figure 25.4 Riprap Lined Channel Design Spreadsheet Data Manning's n Section

Line 45: Manning's n calculated using the Blodgett equation.

Line 46: Manning's n calculated using the Bathurst equation.

Line 47: The effectiveness roughness concentration, which describes the relationship between effective roughness concentration and relative submergence of the roughness bed (HEC-15, pg. 6-2)

Line 48: The Froude number, which is channel velocity divided by the square root of the product of the gravity constant (32.2 ft/s^2) and the average channel depth.

Line 49 - 51: Functions of the Froude number, channel roughness and channel geometry used to calculate the Bathurst n value (line 46).

Bottom Shear:

52	**Bottom Shear**		
53	Shear Velocity, V_* (ft/s)	1.13	1.12
54	Reynolds Number, R_e	9.7E+04	7.7E+04
55	Shield's Parameter, F*	0.084	0.071
56	Safety Factor, SF	1.18	1.12
57	Maximum Shear Stress, τ_d (lb/ft^2)	2.50	2.45
58	Permissible Shear Stress, S_o<=10%, τ_p (lb/ft^2)	9.0	6.05
59	Stability Number, η	0.26	0.38
60	Steepest Channel Side Slope, z	4	4
61	Channel Side Slope Angle, θ (radians)	0.24	0.24
62	Channel Bottom Slope Angle, α (radians)	0.02	0.02
63	Riprap Angle of Repose, ϕ , (radians)	0.730	0.730
64	Weight Vector Angle, B (radians)	0.44	0.60
65	Channel Geometry and Riprap Size Func, Δ	0.99	1.05
66	Permissible Shear Stress, S_o>=5%, τ_p (lb/ft^2)	9.0	5.77
67	Permissible Shear based on Slope, τ_p (lb/ft^2)	9.0	6.0
68	Adjusted Permissible Shear, τ_p/SF (lb/ft^2)	7.5	5.0
69	Bottom Lining Stable (Yes or No)	Yes	Yes
70	Stable D_{50} (ft)	0.35	0.40

Figure 25.5 Riprap Lined Channel Design Spreadsheet Data Bottom Shear Section

Line 53 - 68: These are values and equations used to determine the actual shear stress on the channel bottom and the permissible shear stress for the channel bottom. The process is described in detail in HEC-15, pages 6-3 to 6-5. The spreadsheet compares the two values, and if the actual shear stress is less than the permissible shear stress, then the channel is considered stable (line 69).

Line 70: The riprap D_{50} that will provide a stable straight bottom channel section for the given design flow

Side Shear:

71	**Side Shear**		
72	Channel Side to Bottom Shear Stress Ratio, K_1	0.93	0.93
73	Channel Side Shear Stress, τ_s (lb/ft^2)	2.32	2.27
74	Side Slope Angle, θ (radians)	0.245	0.245
75	Side Slope Angle, θ (degrees)	14.0	14.0
76	Tractive Force Ratio, K_2	0.93	0.93
77	Permissible Side Tractive Force, τ_{ps} (lb/ft^2)	8.34	5.62
78	Side Lining Stable (Yes or No)	Yes	Yes
79	Stable D_{50} (ft)	0.35	0.40

Figure 25.6 Riprap Lined Channel Design Spreadsheet Side Shear Section

Line 72 - 77: These are values and equations used to determine the actual shear stress on the channel side and the permissible shear stress for the channel side. The process is described in detail in HEC-15, pages 6-10 to 6-11.The spreadsheet compares the two values, and if the actual shear stress is less than the permissible shear stress, then the channel is considered stable (line 78).

Line 79: The riprap D_{50} that will provide a stable straight side channel section for the given design flow

Bend Shear:

80	**Bend Shear**		
81	Curvature Radius, R_c (ft)	50	50
82	Ratio of Radius of Curvature to Top Width, R_c/T	3.13	3.19
83	f(Channel Bend and Bottom Shear Stress), K_b	1.81	1.80
84	Shear Stress on the Channel Bottom, τ_b (lb/ft^2)	4.51	4.40
85	Bottom in Bend Stable (Yes or No)	Yes	Yes
86	Shear Stress on the Channel Side, τ_{bs} (lb/ft^2)	4.19	4.09
87	Side in Bend Stable (Yes or No)	Yes	Yes
88	Downstream Length of Protection, L_p (ft)	7	7
89	Addition Freeboard Required, Δd (ft)	0.1	0.1

Figure 25.7 Riprap Lined Channel Design Spreadsheet Data Bend Shear Section

Line 81 - 87: These are values and equations used to determine the actual shear stress on the channel bottom and side, and indicate if the bottom of the bending channel is stable (line 85) and if the side of the bending channel is stable (line 87). The process is described in detail in HEC-15 section 3.4, pages 3-12 to 3-16.

Line 88: This equation determines the length downstream of the end of the channel bend that channel protection will need to be extended to resist bend stresses. See HEC-15, page 3-13.

Line 89: This equation determines the increase in the water surface elevation at the outside of the bend caused by the superelevation of the water surface. See HEC-15, page 3-13.

Example Problem:

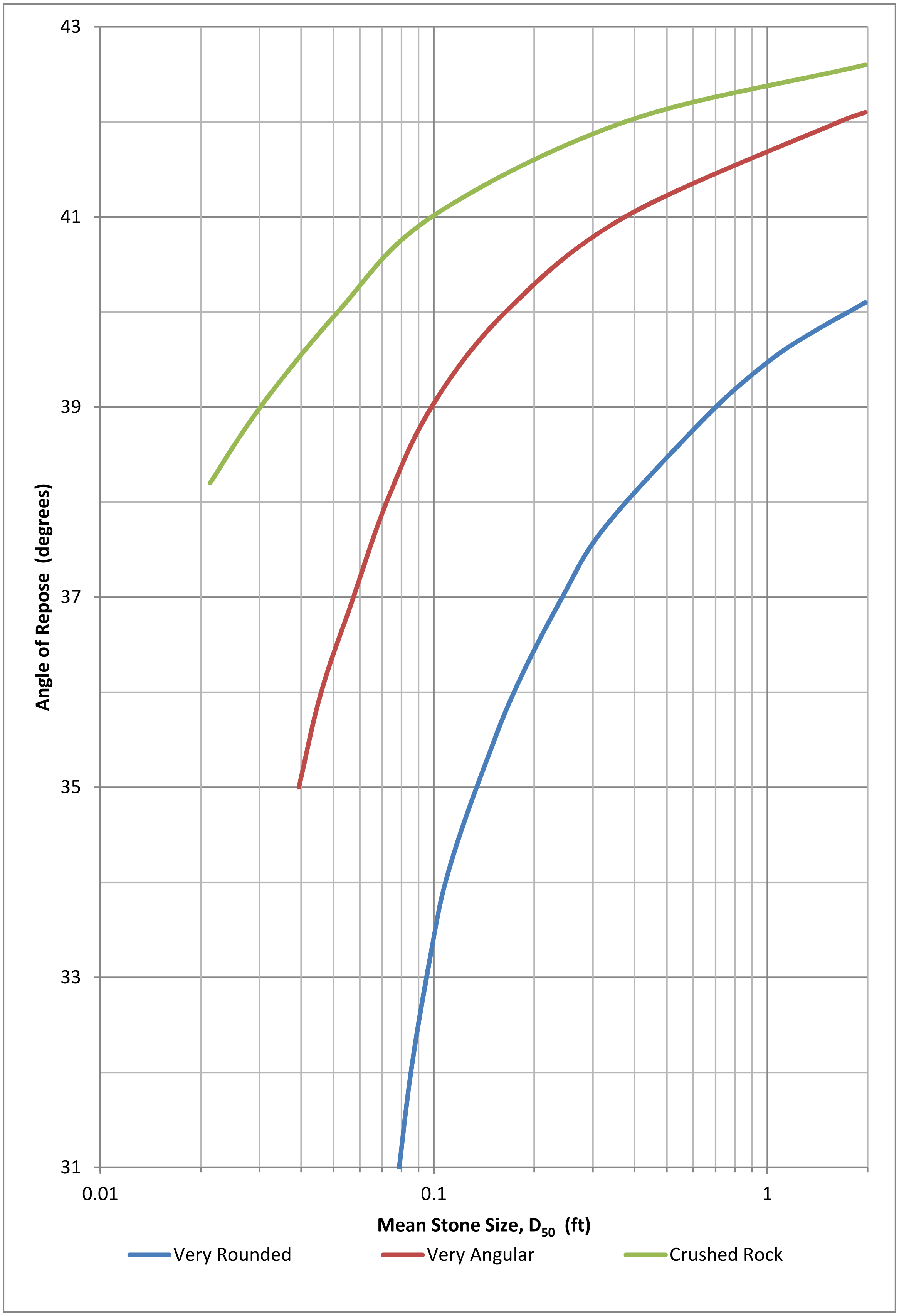
The following example illustrates the design procedure. The data for this example has been entered in the instructions listed above for this attachment. The second column of this example spreadsheet shown in the instructions describes the initial trial and the third column describes the final result of the design procedure. Note that the third column was added to demonstrate how this design spreadsheet works - designers do not need to duplicate each channel section in a set of columns to demonstrate the iterative process.

For the example problem assume the following:

Design Q =	40 cfs
Channel Slope S_o	2 %
Channel Bottom Width =	0 ft
Channel Side Slopes =	4:1
Curvature Radius =	0 ft
Specific Weight of the riprap =	165 lb/ft^3
Riprap angle of Repose =	41.8
SF =	1.2
Curvature Radius =	50 ft.

Enter the data into the second column of the spreadsheet and select light riprap as a first guess. Select the depth of water cell in row 15, and enter your first guess at the water depth in the channel. Note the Calculated Q (ft^3/s) and percent difference between calculated and design flow in rows 24 and 25. Change the depth in row 15 until the percent difference is less than 2%. The cell in row 25 will become green.

If the spreadsheet indicates that, per rows 26 and 27, the bottom and side linings are stable, then you are done unless you want to try a smaller riprap size. In this example, the bottom and sides are not stable after the first trial depth. To correct this, the depth in the last column of this example was changed until the percent difference between the design flow and calculated flow was less than 2%. Rows 26 and 27 indicate that the channel is stable, so the appropriate riprap size for this section is Light Riprap, with a D_{50} of 0.83 ft.

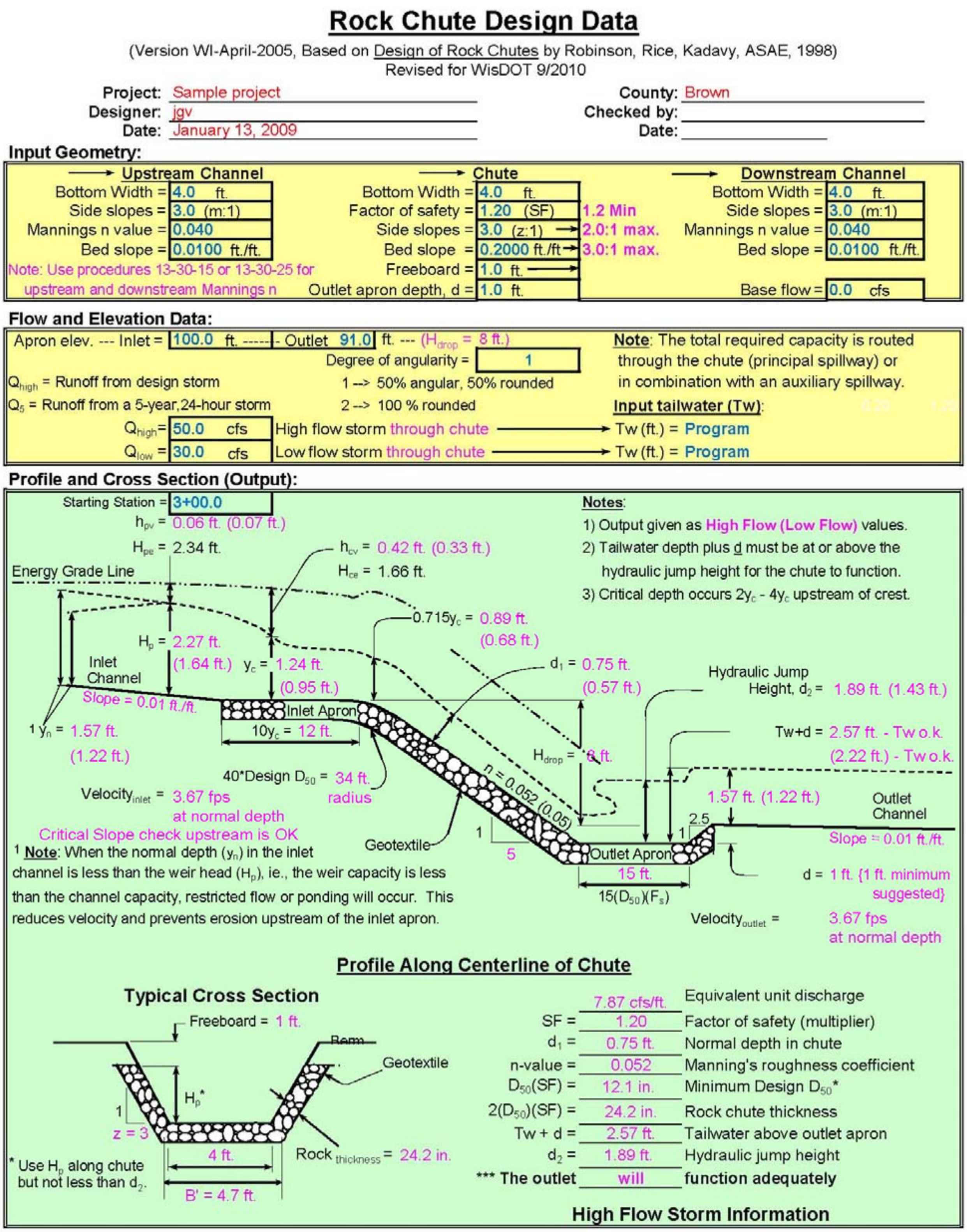


Angle of Repose of Riprap in Terms of Mean Size and Shape of Stone

Note: Use this map as a guide. Check with Soils Engineers or experienced Project Managers or Engineers to determine if angular riprap will be difficult to obtain for a project in a given area.

Rock Chute Design Spreadsheets

Download a zipped working copy of the spreadsheets from the link at the top of FDM 11-30 Attachment 15.2.



Rock Chute Design Data

(Version WI-April-2005, Based on Design of Rock Chutes by Robinson, Rice, Kadavy, ASAE, 1998)
Revised for WisDOT 9/2010

Project: Sample project
Designer: jgv
Date: January 13, 2009
County: Brown
Checked by:
Date:

Input Geometry:

Upstream Channel
Bottom Width = 4.0 ft.
Side slopes = 3.0 (m:1)
Mannings n value = 0.040
Bed slope = 0.0100 ft./ft.
Note: Use procedures 13-30-15 or 13-30-25 for upstream and downstream Mannings n

Chute
Bottom Width = 4.0 ft.
Factor of safety = 1.20 (SF) 1.2 Min
Side slopes = 3.0 (z:1) 2.0:1 max.
Bed slope = 0.2000 ft./ft 3.0:1 max.
Freeboard = 1.0 ft.
Outlet apron depth, d = 1.0 ft.

Downstream Channel
Bottom Width = 4.0 ft.
Side slopes = 3.0 (m:1)
Mannings n value = 0.040
Bed slope = 0.0100 ft./ft.
Base flow = 0.0 cfs

Flow and Elevation Data:

Apron elev. --- Inlet = 100.0 ft. ------ Outlet 91.0 ft. --- (H_{drop} = 8 ft.)
Degree of angularity = 1
1 --> 50% angular, 50% rounded
2 --> 100 % rounded
Q_{high} = Runoff from design storm
Q_5 = Runoff from a 5-year,24-hour storm
Q_{high} = 50.0 cfs High flow storm through chute → Tw (ft.) = Program
Q_{low} = 30.0 cfs Low flow storm through chute → Tw (ft.) = Program
Note: The total required capacity is routed through the chute (principal spillway) or in combination with an auxiliary spillway.
Input tailwater (Tw):

Profile and Cross Section (Output):

Starting Station = 3+00.0
h_{pv} = 0.06 ft. (0.07 ft.)
H_{pe} = 2.34 ft.
h_{cv} = 0.42 ft. (0.33 ft.)
H_{ce} = 1.66 ft.
Energy Grade Line
H_p = 2.27 ft. (1.64 ft.)
y_c = 1.24 ft. (0.95 ft.)
0.715y_c = 0.89 ft. (0.68 ft.)
d_1 = 0.75 ft. (0.57 ft.)
Inlet Channel
Slope = 0.01 ft./ft.
Inlet Apron
10y_c = 12 ft.
1 y_n = 1.57 ft. (1.22 ft.)
40*Design D_{50} = 34 ft. radius
Velocity$_{inlet}$ = 3.67 fps at normal depth
Critical Slope check upstream is OK
Geotextile
H_{drop} = 8 ft.
n = 0.052 (0.05)
1
5
Outlet Apron
15 ft.
15(D_{50})(F_s)
Hydraulic Jump Height, d_2 = 1.89 ft. (1.43 ft.)
Tw+d = 2.57 ft. - Tw o.k. (2.22 ft.) - Tw o.k.
1.57 ft. (1.22 ft.)
2.5
1
Outlet Channel
Slope = 0.01 ft./ft.
d = 1 ft. {1 ft. minimum suggested}
Velocity$_{outlet}$ = 3.67 fps at normal depth

Notes:
1) Output given as High Flow (Low Flow) values.
2) Tailwater depth plus d must be at or above the hydraulic jump height for the chute to function.
3) Critical depth occurs 2y_c - 4y_c upstream of crest.

1 Note: When the normal depth (y_n) in the inlet channel is less than the weir head (H_p), ie., the weir capacity is less than the channel capacity, restricted flow or ponding will occur. This reduces velocity and prevents erosion upstream of the inlet apron.

Profile Along Centerline of Chute

Typical Cross Section
Freeboard = 1 ft.
Berm
Geotextile
H_p*
1
z = 3
4 ft.
B' = 4.7 ft.
Rock$_{thickness}$ = 24.2 in.
* Use H_p along chute but not less than d_2.

	7.87 cfs/ft.	Equivalent unit discharge
SF =	1.20	Factor of safety (multiplier)
d_1 =	0.75 ft.	Normal depth in chute
n-value =	0.052	Manning's roughness coefficient
D_{50}(SF) =	12.1 in.	Minimum Design D_{50}*
2(D_{50})(SF) =	24.2 in.	Rock chute thickness
Tw + d =	2.57 ft.	Tailwater above outlet apron
d_2 =	1.89 ft.	Hydraulic jump height
*** The outlet	will	function adequately

High Flow Storm Information

Rock Chute Design - Plan Sheet

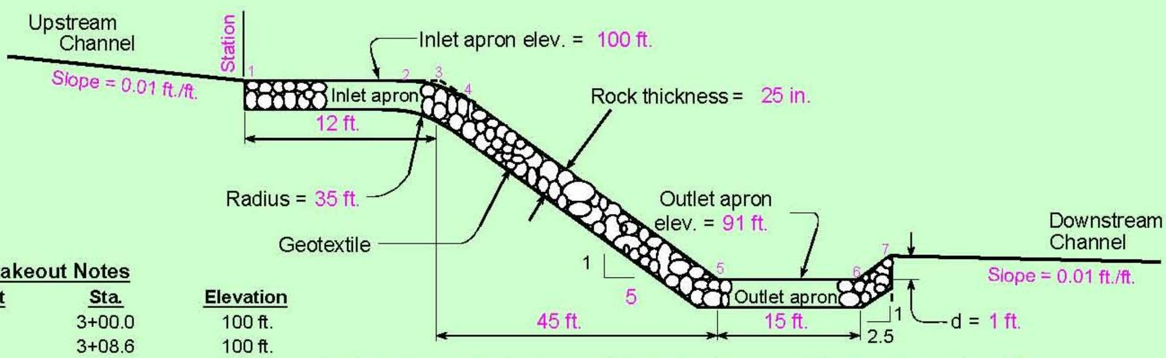
(Version WI-April-2005, Based on Design of Rock Chutes by Robinson, Rice, Kadavy, ASAE, 1998)
Revised for WisDOT 9/2010

Project: Sample project **County:** Brown
Designer: jgv **Checked by:**
Date: 1/13/2009 **Date:**

Design Values		Plan Values	
12.1 in.	D_{50} dia. =	12.5	in.
24 in.	Rock chute thickness =	25	in.
12 ft.	Inlet apron length =	12	ft.
15 ft.	Outlet apron length =	15	ft.
34 ft.	Radius =	35	ft.

Quantities[a]
Riprap = 148 yd^3
Geotextile = 271 yd^2

***Notes**: [a] Rock and geotextile quantities are determined from the x-section below (neglect radius).*



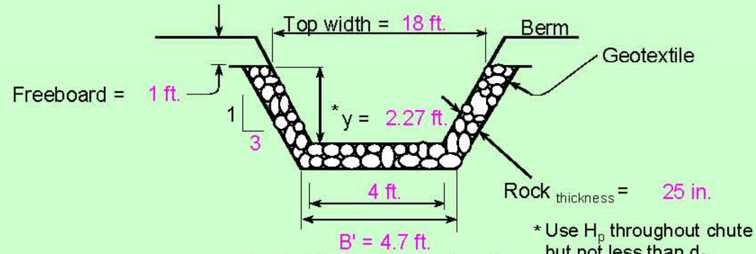
Profile Along Centerline of Rock Chute

Stakeout Notes

Point	Sta.	Elevation
(1)	3+00.0	100 ft.
(2)	3+08.6	100 ft.
(3)	3+12.0	99.8 ft.
(4)	3+15.4	99.3 ft.
(5)	3+57.0	91 ft.
(6)	3+72.0	91 ft.
(7)	3+74.5	92 ft.

****Note**: The outlet will function adequately**

Rock gradation envelope can be met with DOT Medium Riprap Gradation



Rock Chute Cross Section

Profile, Cross Sections, and Quantities

	Sample project		Date	File Name
	Brown County	Designed jgv		Drawing Name
		Drawn		
		Checked		
		Approved		Sheet __ of __

Rock_Chute.xls
for construction plan

Rock Chute Design Construction Detail

(Version WI-April-2005, Based on Design of Rock Chutes by Robinson, Rice, Kadavy, ASAE, 1998)
Revised for WisDOT 9/2010

Project: Sample project **County:** Brown
Designer: jgv **Checked by:** ____________
Date: 1/13/2009 **Date:** ____________

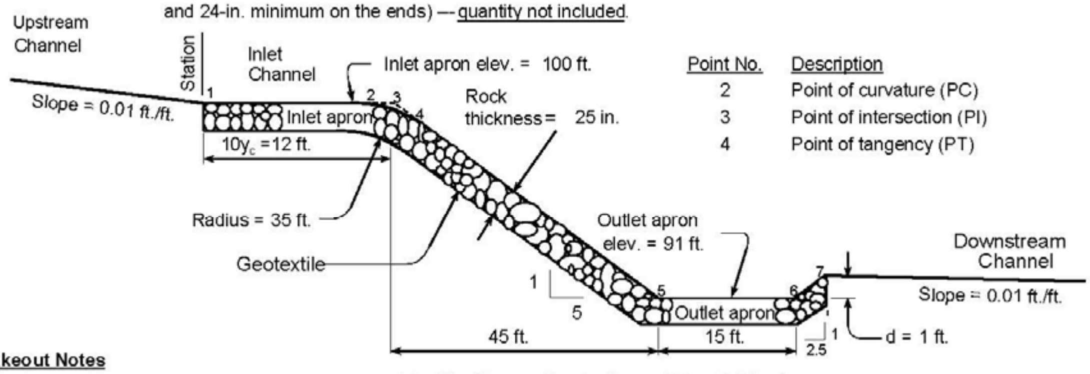
Design Values

D_{50} dia. = 12.5 in.
$Rock_{chute}$ thickness = 25.0 in.
Inlet apron length = 12 ft.
Outlet apron length = 15 ft.
Radius = 35 ft.

Quantities[a]

Rock = 148 yd^3
Geotextile (WCS-13)[b] = 271 yd^2

Notes: [a] Rock and geotextile quantities are determined from x-section below (neglect radius).
[b] Geotextile shall be overlapped (18-in. minimum) and anchored (18-in. minimum along sides and 24-in. minimum on the ends) — quantity not included.

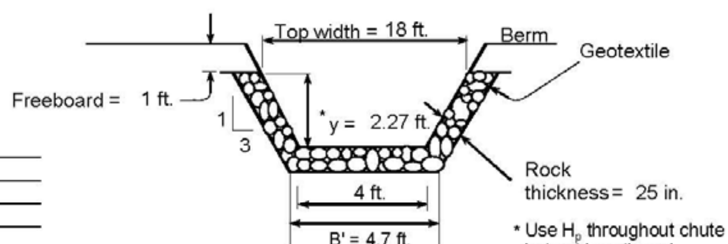


Profile Along Centerline of Rock Chute

Stakeout Notes

Point	Sta.	Elevation
(1)	3+00.0	100 ft.
(2)	3+08.6	100 ft.
(3)	3+12.0	99.8 ft.
(4)	3+15.4	99.3 ft.
(5)	3+57.0	91 ft.
(6)	3+72.0	91 ft.
(7)	3+74.5	92 ft.

Notes:
Rock gradation envelope can be met with
DOT Medium Riprap Gradation



Rock Chute Cross Section

Profile, Cross Sections, and Quantities

		Date	
	Sample project	Designed jgv	File Name
		Drawn	Drawing Name
	Brown County	Checked	
		Approved	Sheet _ of _